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Effect of Stress on the Lüders Band Velocity in Low Carbon Steels

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Inglewood, California

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ABSTRACT

The Lüders band propagation rate, S_L, in low carbon steel can be considered to obey the relation,

$$S_L = S_0 \exp -\left(H(\tau^*)/kT\right)$$

where S_0 is approximately a constant, and $H(\tau^*)$ is the activation energy of the process, and represents a decreasing function of the effective stress, τ^* (given by the difference between the applied stress and the long-range internal stress). Available data on the effect of stress on Lüders band velocity is correlated on the basis of this relationship. The fact that the activation volume derived from this correlation is independent of structure, and is the same as that for dislocation mobility and other deformation phenomena in iron and steel, suggests that the rate-controlling mechanism is thermally-activated overcoming of the Peierls-Nabarro stress.

EFFECT OF STRESS ON THE LÜDERS BAND VELOCITY IN LOW CARBON STEELS

In a recent paper, Butler [1962 (Ref. 1)] indicated that the Lüders band velocity, $\dot{s}_L$, in low carbon steel could be expressed by the relationship originally proposed by Fisher and Rogers [1956 (Ref. 2)]:

$$\dot{s}_L = A - \frac{B}{\sigma} \tag{1}$$

where σ is the applied tensile stress, and A and B are material constants that depend on the structure i.e., on grain size, carbon content, and heat treatment. Eq. (1) is based on an analysis by Fisher [1955 (Ref. 3)] of the thermally-assisted tearing of dislocations from an interstitial atmosphere. On the other hand, Hahn [1962 (Ref. 4)], proposed an empirical relationship of the form

$$\dot{s}_L = \left(\frac{\sigma}{\sigma_o}\right)^m \tag{2}$$

where m and σ_o vary with structure. None of the above authors has provided an explanation of the role that structure plays in the propagation of a Lüders band.

From a consideration of the dynamic aspects of the plastic deformation of iron and steel, Conrad [1961 and 1963 (Refs. 5, 6, and 7)] has suggested that the strain rate $\dot{\epsilon}$ is given by

$$\dot{\epsilon} = \nu \exp-\left[\frac{H(\tau^*)}{kT}\right] \tag{3}$$

where ν is a frequency factor that includes: the number of places where thermal activation may occur, the strain per successful thermal fluctuation, and an entropy term. $H(\tau^*)$ is the enthalpy (energy) of activation, which is a decreasing function of the effective shear stress, τ^*, given by the difference

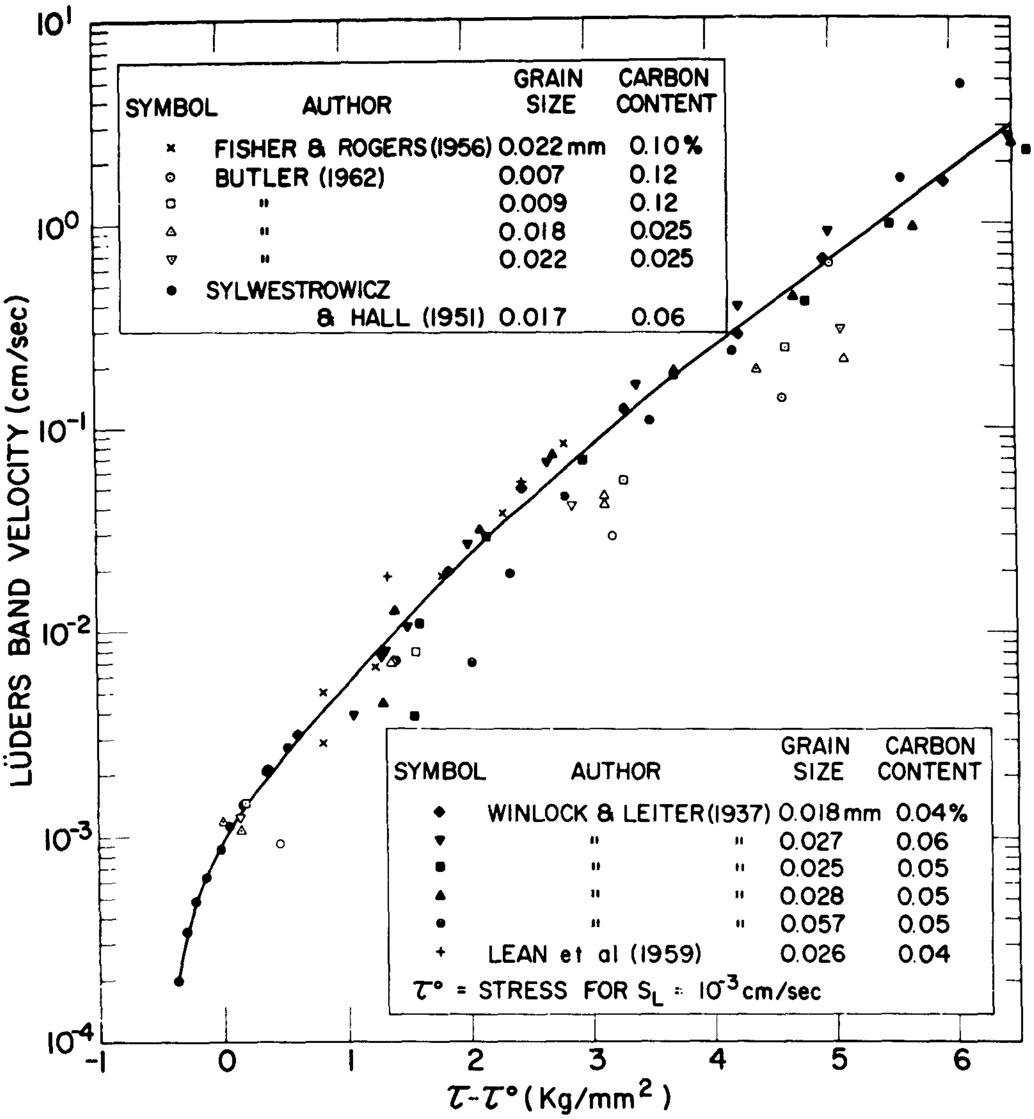

Fig. 1. Effect of Stress on Lüders Band Velocity at 300°K in Low Carbon Steel

between the applied stress[1], τ, and the long-range internal stress, τ_μ (proportional to the shear modulus, μ). τ^* is also termed the thermal component of the stress, and is a function of the temperature and the strain rate. τ_μ is termed the athermal component, is a function of the structure, is independent of strain rate, and varies with temperature only as the shear modulus varies with temperature. To eliminate the athermal component of the stress in any consideration, some reference stress, τ^{o}, referred to a fixed temperature and strain rate, is subtracted from the applied stress, τ; that is,

$$\tau(T, \dot{\epsilon}) - \tau^{o}(T, \dot{\epsilon}_{o}) = \Delta\tau^{*}(T, \dot{\epsilon}) \tag{4}$$

Assuming that the propagation of a Lüders band is controlled by the same dislocation mechanism that controls the plastic strain rate following the yield point elongation [Conrad 1961 (Ref. 5)], then

$$\dot{s}_{L} = \dot{s}_{o} \exp-\left[\frac{H(\tau^{*})}{kT}\right] \tag{5}$$

where $\dot{s}_{o}$ is approximately a constant. If the velocity is plotted versus the quantity, $\tau - \tau^{o}$, all of the data on the effect of stress on Lüders band velocity at constant temperature would be expected to lie on one curve. That this is the case is shown in Fig. 1[2]. Here, τ^{o} is taken as the stress that gives a Lüders band velocity of 10^{-3} cm/sec at 300°K.

Rearranging Eq. (5) and differentiating with respect to stress, one obtains

$$-\frac{dH}{d\tau^{*}} = kT\left(\frac{\partial \ln \dot{s}_{L}}{\partial\tau^{*}}\right)_{T} = v^{*} \tag{6}$$

[1]For the b. c. c. metals one can assume that $\tau = 1/2\ \sigma$.

[2]The Lüders band velocity was calculated from the data of J. Winlock and Leiter, 1937 (Ref. 8). Sylwestrowicz and Hall [1951 (Ref. 9)], and Lean, Plateau and Crussard, [1959 (Ref. 10)] from the well-known relationship $\dot{s}_{L} = (\dot{\epsilon}\ell)/(n\epsilon_{L})$ where ℓ is the specimen length, n is the number of Lüders bands (assumed to be two) and ϵ_{L} is the Lüders strain.

where v* is termed the activation volume. In Fig. (2) it is seen that the activation volumes obtained by graphical differentiation of the curve of Fig. (1) are in good agreement with those obtained from other data [Conrad 1961 and 1963 (Refs. 5, 6, and 7)] on the plastic flow of iron and steel. In Fig. 2 it is assumed that $\tau^* \simeq 0$ at $\dot{s}_L = 10^{-4}$ cm/sec.

The above indicates that the effect of stress on Lüders band velocity can be described by Eq. (5), and that, as postulated previously (Ref. 5), the same dislocation mechanism is controlling during Lüders band propagation as during homogeneous plastic flow. Furthermore, for the steels considered,

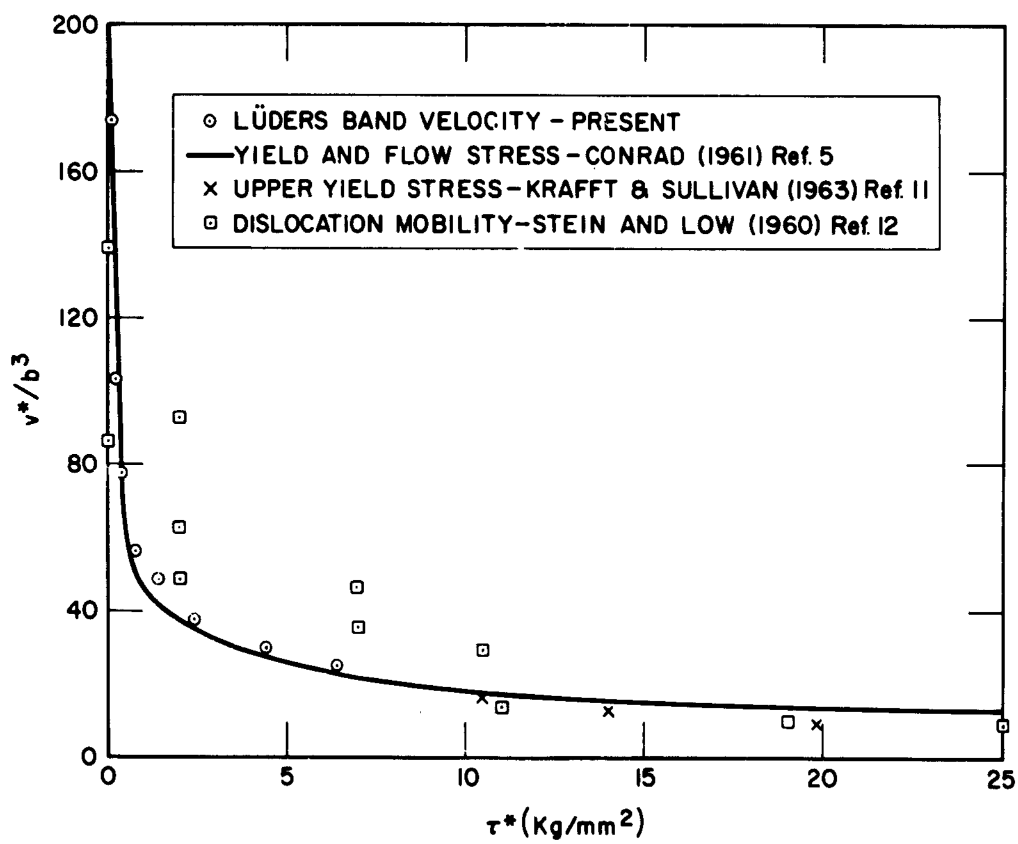

Fig. 2. Variation of the Activation Volume, Divided by the Burgers Vector Cubed, with Stress for Iron and Steel

the effect of structure (strain, grain size, carbon content, etc.) is principally through the long-range stress fields opposing the motion of dislocations, rather than through any direct effect on the controlling mechanism. This and other work (Refs. 5, 6, and 7) suggest that the rate-controlling mechanism during the yielding and flow of iron and steel at low temperatures ($T < 0.2T_m$) is thermally-activated overcoming of the Peierls-Nabarro stress.

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